WL-TR-94-3157

FATIGUE FAILURE ANALYSIS OF POLYCARBONATE TRANSPARENCIES IN DIFFERENT ENVIRONMENTAL CONDITIONS

PURDUE RESEARCH FOUNDATION
DEPARTMENT OF ENGINEERING
HAMMOND, IN

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FINAL REPORT FOR PERIOD 05/18/92 - 10/01/94

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The investigation completed under the existing contract determines the extruded polycarbonate fatigue life dependency on elevated and cooling temperatures. The specimens were manufactured from the ½-inch flat polycarbonate sheet which is used as a structural component in laminates for some F-16 aircraft canopies. The results of the investigation showed that the elevated temperature is extremely dangerous. Fatigue lives of the specimens tested on different combinations of load and elevated temperature levels were always significantly (up to 10 times) less compared to those tested under the same load levels at room temperature. The surface topography failure modes also were different: ductile under room temperature and brittle under elevated temperatures. The investigations under cooling temperatures proved that the resistance to fatigue failure is substantially greater than that for room temperature.

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PREFACE

The efforts reflected in the project were performed by Purdue University Calumet, Department of Engineering, Hammond, Indiana under Air Force Contract F33615-92-C-3403. The title of the project: "Fatigue Failure Analysis of Polycarbonate Transparencies in Different Environmental Conditions." The project was sponsored by the Flight Dynamics Directorate, Wright Laboratory, Wright Patterson Air Force Base, Dayton, Ohio. Air Force administrative direction and technical support were provided by Ms. Lorene Garrett and Mr. Richard Smith, WL/FIVR.

The work was performed during the period 5/18/92 - 10/1/94 (including no cost extension additional time). Purdue University Calumet supervision and technical effort was provided by Professor Yulian Kin, Department of Engineering. Professor Kin was principal investigator of the project. Some data were presented at the Conference on Aerospace Transparent Materials and Enclosures, San Diego, CA, August, 1993 [1].

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1. INTRODUCTION

1.1 Background

Aircraft transparencies are high life cycle cost items for the Air Force that necessitate frequent replacement. One of the failure modes encountered most frequently in the field is polycarbonate fracture.

There are, for example, complaints of F-16 transparency failures in flight [2,3,4]. The nature of failures is not quite clear, but some evidence implies that transparency life is limited by fatigue. At present, no experimental fatigue statistics on the composite material used for F-16 transparency were found. Therefore, today no data exist that allow life prediction for a canopy based on fatigue or crack propagation, and thus no basis for comparison of new materials and designs taking into consideration their resistance to fatigue and crack propagation.

The F-16 transparency is manufactured from a laminated composite material. Components of the composite are an acrylic face ply, a polycarbonate ply, interlayers, and coatings with some variations among the vendors. Design of the canopy allows to unload an acrylic ply (Figure 1) and that is why the structural polycarbonate ply of the composite was the primary concern during fatigue investigation in this project.

Note that a long-term fatigue test procedure requires the breaking of 20 to 30 identically prepared specimens and 15 days to 1 month to complete. Thus, manufacturers do not perform a conventional fatigue test in spite of its obvious utility. Therefore, there is a definite need for an accelerated test which can be completed in approximately one shift.

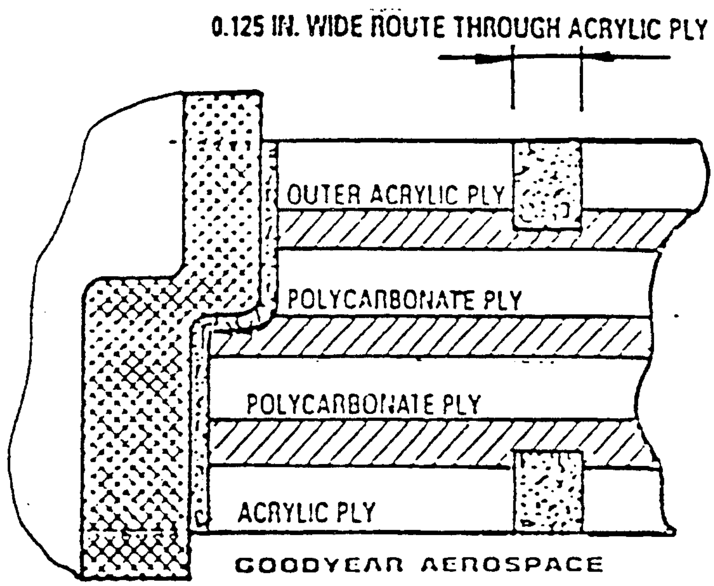


Figure 1. Schematic Canopy Design

The fatigue tests results gained in this study can be useful to verify the precision of the accelerated test procedure developed.

Previous research completed by Purdue under the Summary Faculty Research Program and subsequent minigrants initiated investigation of fatigue and fracture simulations of polycarbonate coupons in laboratory conditions using long-term and accelerated testing techniques. The development of the investigation procedures was continued in this project and previously collected information was verified. It is also necessary to simulate actual service conditions to obtain fatigue crack initiation and propagation parameters in order to enable more reliable predictions of canopy failures and service life. Therefore, the fatigue properties of polycarbonate under elevated and cooling temperatures and different load levels were investigated in this effort.

1.2 Objectives

- Development of a detailed procedure to conduct fatigue and fracture tests of polycarbonate coupons under different environment simulations.

- Manufacturing of the specimens and conduction of the tests.

- Analysis of the test results and comparison with the data of previous investigations under room temperatures. The project also includes some investigations of fatigue resistance of polycarbonate coupons with different thickness, and study of fatigue life under different load frequency.

1.3 Scope and Summary

The investigation completed under the existing contract determines the extruded polycarbonate fatigue life in room conditions and under elevated and cooling temperatures. According to the procedure developed, this investigation is conducted on 0.5-inch polycarbonate coupons with and without stress concentration. To support these experiments, Purdue Calumet purchased an MTS environment chamber and a new controller at a cost of approximately $20,000. All necessary expenses related to the equipment installation, calibration, and training were paid by Purdue. The University also covered the expenses for the unexpectedly long time experiments under cooling temperature and the high consumption of liquid nitrogen. The results of the investigation showed that the elevated temperature is extremely dangerous. Fatigue lives of the specimens tested on different combinations of load and elevated temperature levels were always significantly (up to 10 times) less compared to those tested under the same load levels at room temperature. The surface topography failure modes also were different -- ductile under room temperature and brittle under elevated temperature. The tests under cooling temperature proved that the resistance to fatigue failure is substantially greater than that for room temperature. The results of the completed tests underline the fact that elevated temperatures greatly decrease the fatigue resistance of the polycarbonate canopy. Due to unexpectedly long tests under cooling temperatures, the investigation of chemical affection was beyond time limits of this project. It is important to continue the investigation for aged polycarbonate, especially aged under high temperature, and combined with different chemicals and solutions.

2. MATERIAL AND SPECIMENS

The material used was supplied by Wright-Patterson Air Force Base. The testing coupons were cut from the 0.5-inch polycarbonate sheets. The sheets were extruded, pressed and polished in accordance with the military specification MIL-P-83310.

The configuration and dimensions of the test specimens are shown in Figure 2. The specimens were cut by a fine band saw with the lowest possible speed and using a cooling liquid. The holes were also drilled very slowly with intermittent stops and using cooling liquid. The hole edge burrs were not removed to prevent invisible damage. The cut specimens were divided into two groups. In the first group the edges were left as they were after machining. All machined specimens in the second group were polished on the sides and edges by carbimet paper disks for automet attachment. The 8-inch x 2.5-inch self-adhesive back disks No. 30-5158-120, grits 120-180 were manufactured by Buehler Ltd. The 3/4-inch core-series 17-0310 scotch tape was used to protect from damage the gripping area of the specimens. The scotch tape was bonded in three layers on each end of the specimen. It took usually about 10 minutes after the beginning of the test to adjust the loading regime assigned due to formation of "bed" by hard jig rollers in the soft tape layers.

3. EQUIPMENT

The flexure fatigue tests were conducted on an MTS machine (Figure 3) using four point MTS flexure system to provide pure bending. Actual fatigue machine with the environmental chamber, loading diagram, and flexure figures inside of the chamber, are shown in Figures 4 and 5.

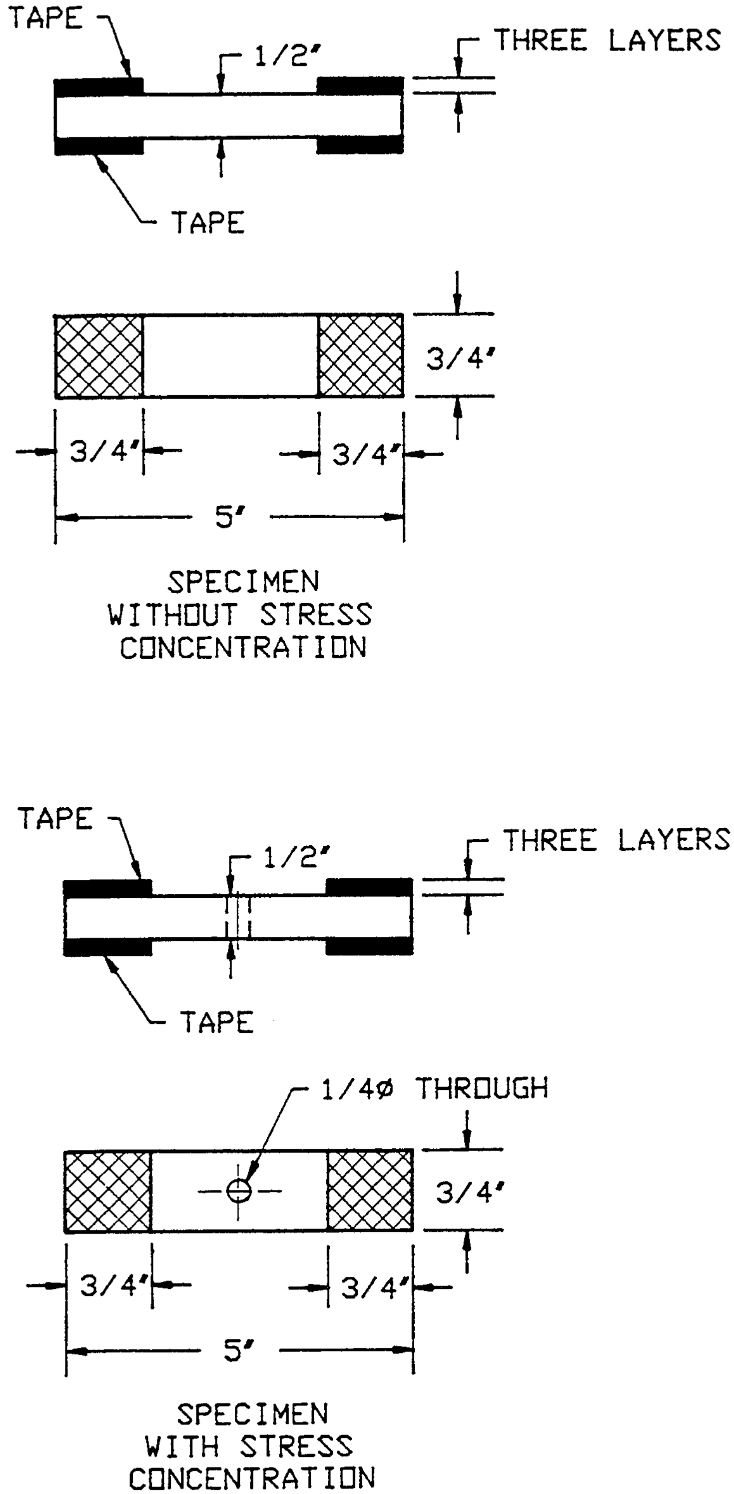


Figure 2. Speciments Used in Study

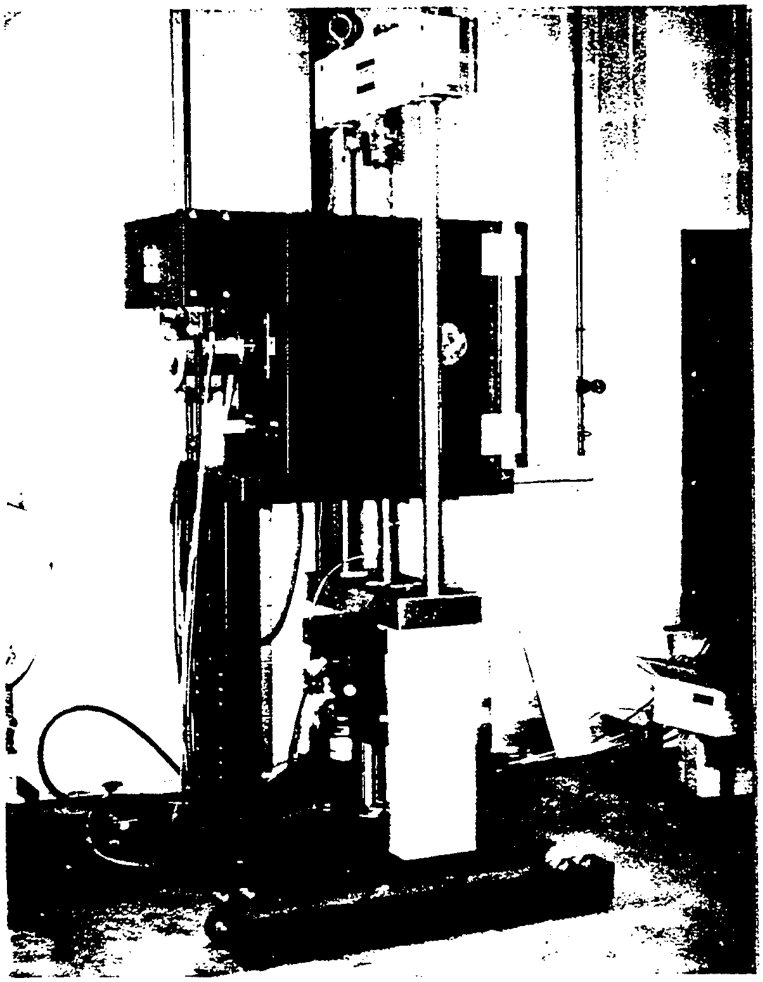
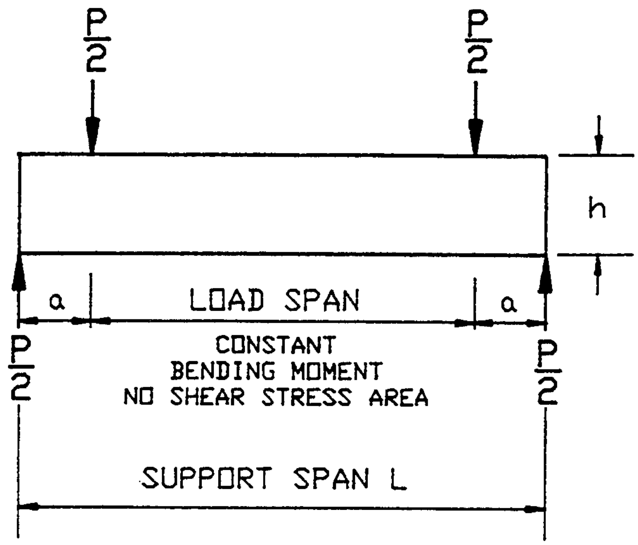


Figure 3. MTS Fatigue Machine with the Environmental Chamber



MAX DEFLECTION:

$$Y_{MAX} = \frac{Pa}{48EI}(4a^2 - 3L^2)$$

MAX STRESS:

$$MAX = \frac{3P(a)}{bh^2}$$

Figure 4. Loading Diagram

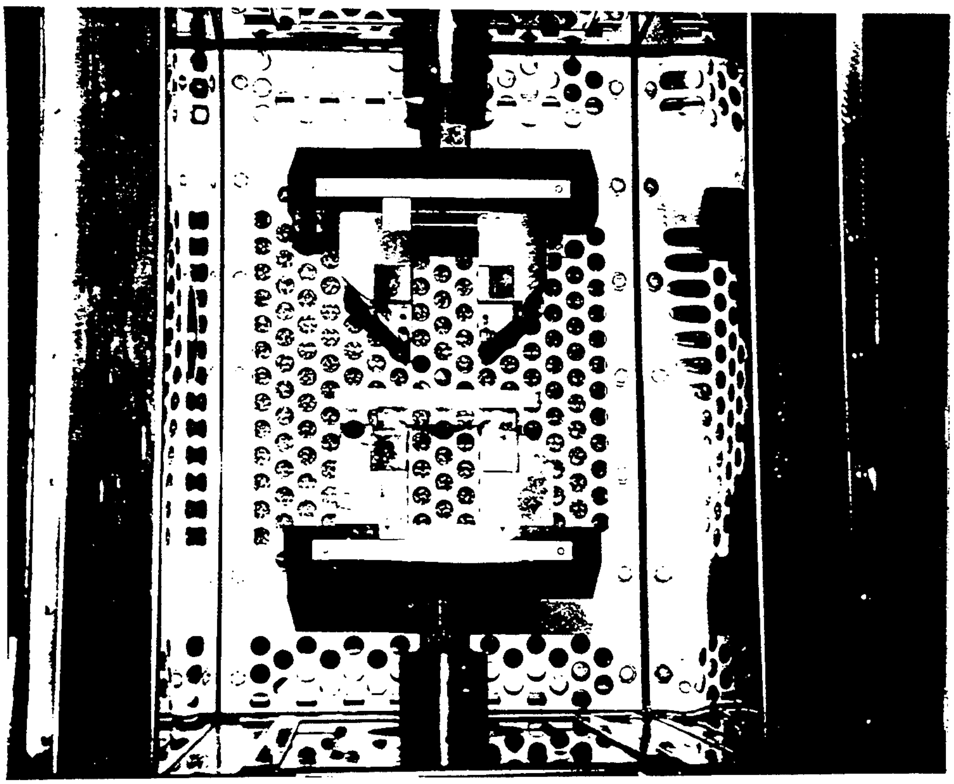


Figure 5. Flexure Fatigue Fixture Inside of the Environmental Chamber

Note that load reading on the MTS machine controller is P, in other words the load reading on the machine device doubled comparing with that shown in Figure 3. The appropriate support and load spans were selected to provide minimum possible deflection of the specimens. The small deflections provide more stable position of the specimens between jig rollers and permit to assign greater testing frequency.

The flexure fatigue tests under different temperatures were conducted in the MTS environmental chamber (Figures 3 and 5).

4. FAILURE CRITERIA

Different options were analyzed prior to the assigning of a final failure criterion.

1. Certain percentage load drop can be considered as failure during constant stroke and hence controlled specimen deflection testing. This testing mode permitted crack growth observation and decreased creep influence. But non uniform and inconsistent load drop registered during preliminary tests did not permit to make a clear test result interpretation. Also constant deflection conditions do not reflect the actual situation.

2. During constant load testing the complete separation or certain percentage crack propagation can be considered as failure and the preliminary testing showed that the resultant scatter was significantly less than in the constant stroke test. The constant load mode also better simulates the actual loading.

3. Crazing and therefore visibility lost definitely can be considered as failures for the canopy material.

4. A minute crack detected by eye can also be considered as a failure because there are no data on how fast an initial crack will propagate in the polycarbonate sheet tested.

Taking this into consideration, the decision was made to perform the test under constant load regime and develop S-N diagrams with different failure criteria (complete separation or 80% crack propagation over the specimen width, crazing, minute crack formation).

5. LONG-TERM TEST PROCEDURE (ROOM TEMPERATURE)

The pulsating bending tests were conducted in the laboratory atmosphere (about 70^{0}F and 50% relative humidity). The tests were run at least at four load levels and at least four specimens were tested at each load level. The regimes are given in Table 2. The ratio of minimum load over maximum load was 0.2 for all tests. The testing time per day was not more than 10 hours, hence the possible influence of stops was not considered in this project. The tests continued until specified damage were observed but not longer than 10^6 cycles. Regression analysis was used to treat the test results.

6. LONG-TERM TEST RESULTS AND DAMAGE DESCRIPTION (ROOM TEMPERATURE)

The test results of 0.5-inch coupons are plotted in Figures 6, 7, and 8. The cracks were always started at the bottom tensile zone of the specimens. In all solid specimens with the exception of two cases the cracks propagated from the edge toward the center of the coupons tested. In all specimens with stress concentrators the cracks propagated from the hole edges toward the specimens sides (Figure 9). Usually craze (minute crack) spot preceeds the crack formation and propagates ahead of the crack tip, and it can be concluded that damage mechanism is very similar to that described in [5] for crack propagation in polysterene under fatigue loading. When the visible separate minute cracks were detected during the high load level testing, the massive craze zones developed after that very fast. It can be noted that the lives of specimens are significant after the massive craze spot formation until complete breakage. For low load levels no massive craze zones were observed. But again in many cases after the initiated crack was easily visible, we could detect a substantial number of cycles until complete breakage of the specimen. Comparison of the S-N diagrams in Figures 6, 7, and 8 shows that the stress concentration influence on fatigue life of the tested polycarbonate specimens is significant. The specimens without stress concentration have much longer fatigue life.

Comparison of fatigue lives for the 0.5-inch and 0.25-inch thickness specimens tested under the same stress is given in Figure 10. The test results show that the life of the thinner material is less. The breakage of the 0.25-inch specimen occurred almost without any "warning." Complete separation was approached very fast after the crack initiation.

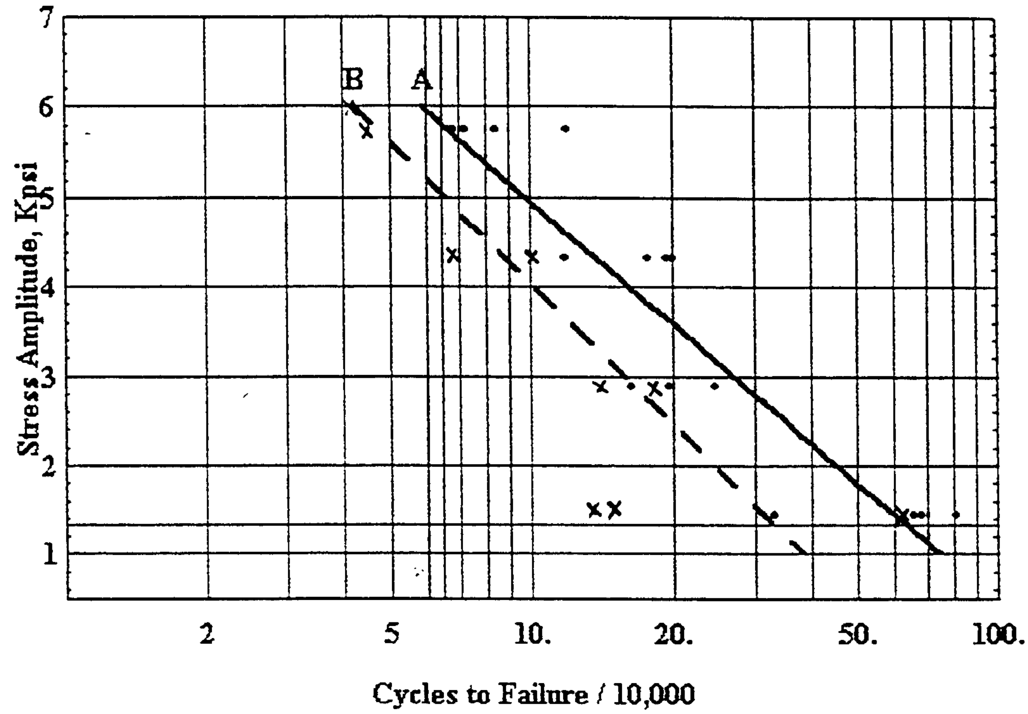


Figure 6. S-N Diagram for the Polycarbonate Specimens with Stress Concentrators.

A - Complete Separation
B - Crack Initiation
o - Failure
x - Crack Initiation

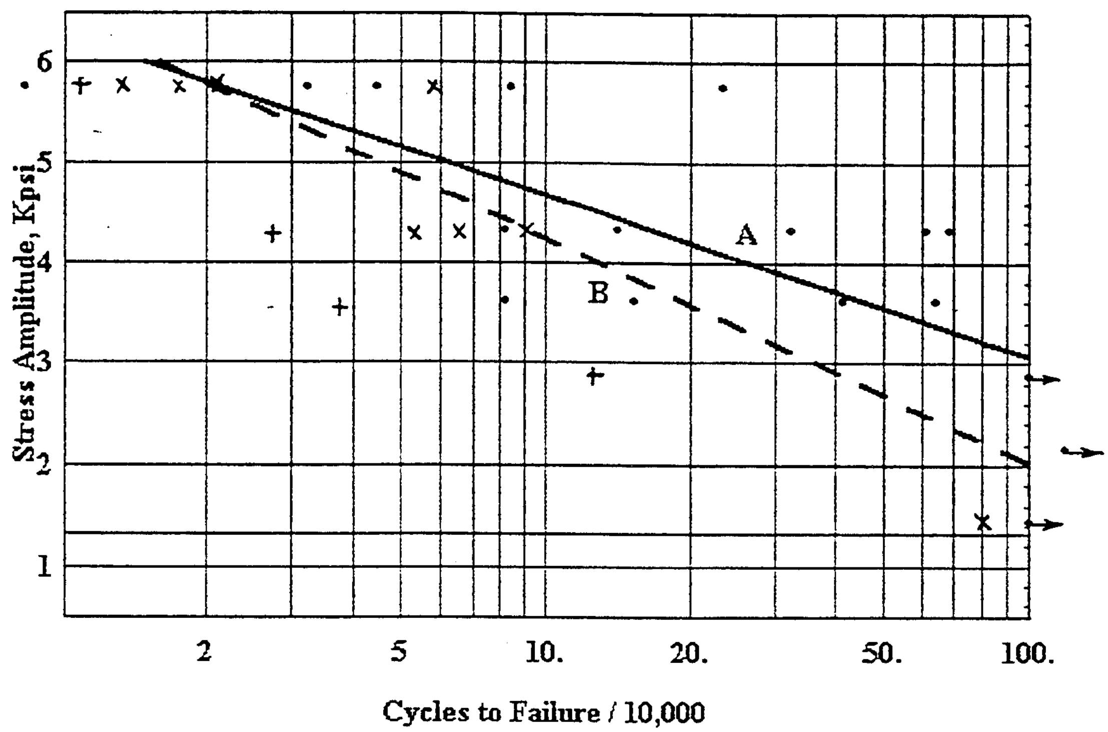


Figure 7. S-N Diagram for the Solid Polycarbonate Specimens

A - Complete Separation
B - Crack Initiation
o - Failure
x - Crazes
+ - Specimens with not Polished Edges

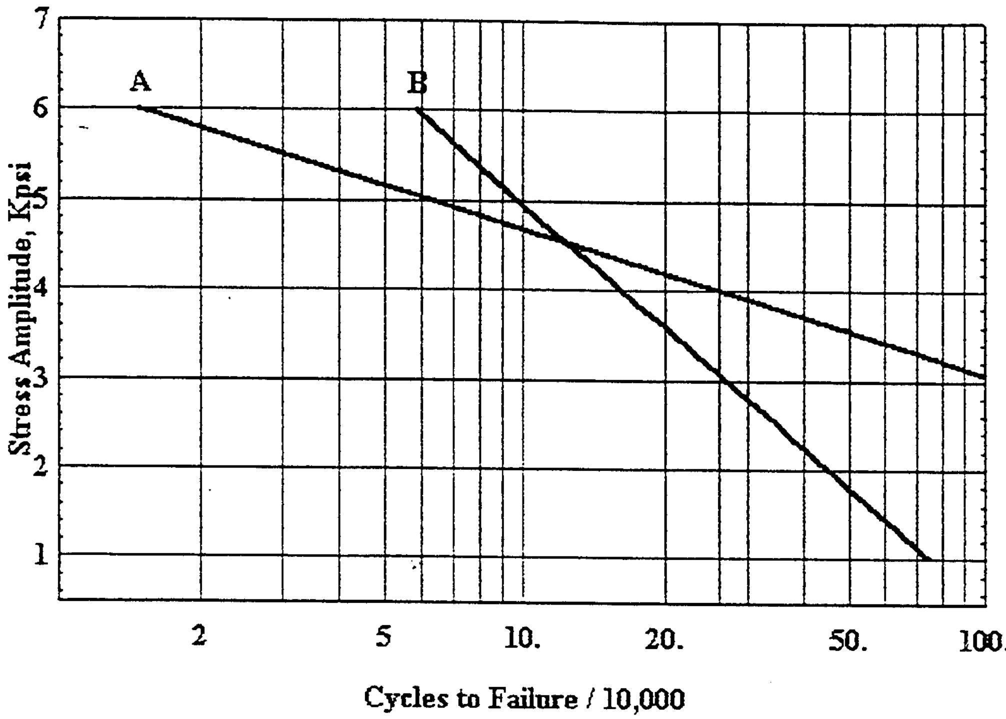


Figure 8. S-N Diagram for the Polycarbonate Specimens with and without Stress Concentrators.

A - without Stress Concentrators
B - with Stress Concentrators

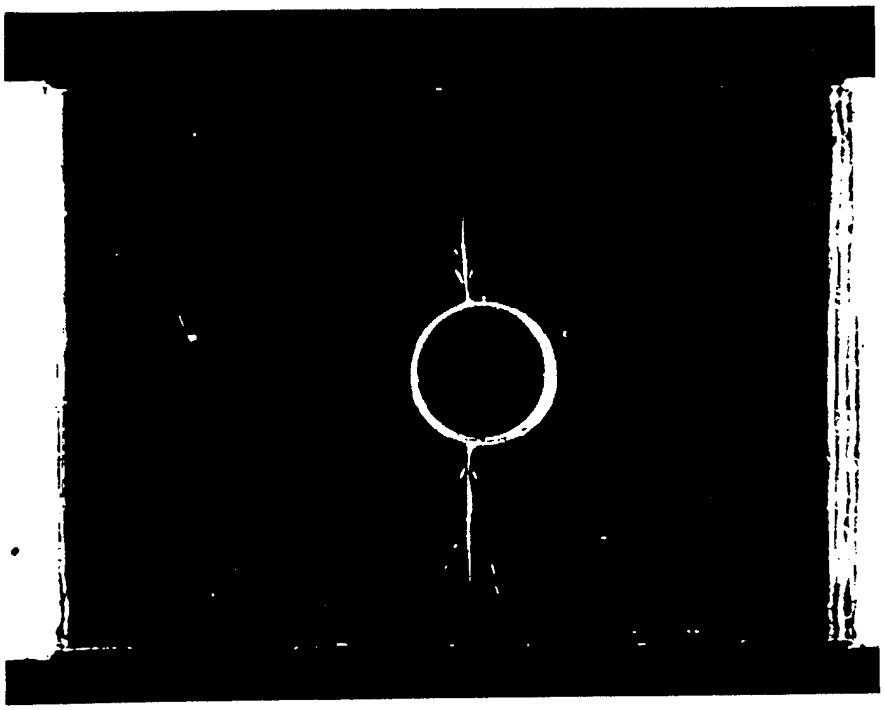


Figure 9. Crack Propagation in the Polycarbonate Specimen with the Stress Concentrator

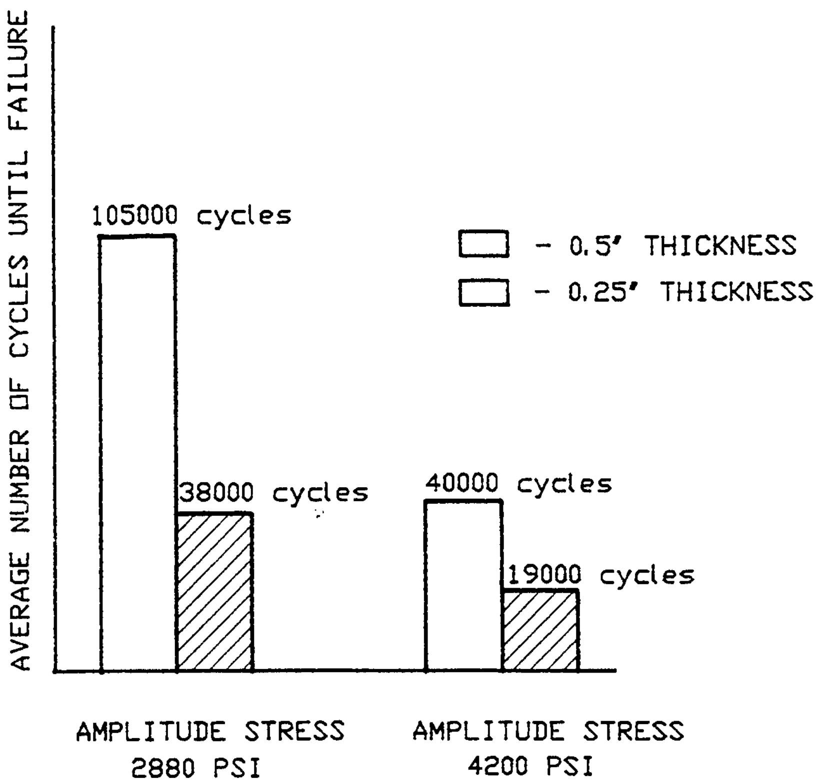


Figure 10. Comparison of Fatigue Lives of the spesimens with Different Tickness. Variable Bending. Specimens with Stress Concentration. Frequency 5 Hz. Ten specimens tested in each group

The results of fatigue tests conducted at different load frequencies are given in Table 1. The results show that the properties of the material tested are time dependent. The number of cycles until complete separation strongly depends on frequency, but specimen life in hours was almost the same for the specimens tested at the same load level and different frequencies. We should consider providing optimal usage and efficiency of the polycarbonate parts.

7. ACCELERATED FATIGUE TEST

It appears that the fatigue properties of polycarbonate sheets vary significantly from sheet to sheet. Therefore, it is important to have a mechanism which permits quality control of polycarbonate sheets, detects deviations in the manufacturing process, and enables preliminary estimates of the design changes. The accelerated procedure proposed in this project is based on Locaty's accelerated method [6] used as prototype. The major objectives of the study was development of a detailed procedure of the accelerated fatigue test for coupons cut from structural polycarbonate sheets.

The Locaty's accelerated fatigue method is based on the concept of cumulative fatigue damage [7] considering $\sum \left(\frac{n_i}{N_i}\right) = 1\text{-}5$, where n_i is the number of cycles which the specimen worked in the specified test regime, and N_i is the number of cycles which the specimen could potentially work in accordance with the fatigue curve received from the long-term fatigue tests of the same type of specimens. The loading program and the treatment of results are presented in Figures 11 and 12. Figure 11 shows three fatigue curves received from a long-term fatigue test. From Figure 11, the magnitudes of

$$\sum \left(\frac{n_i}{N_i}\right)_A ; \qquad \sum \left(\frac{n_i}{N_i}\right)_B ; \qquad \sum \left(\frac{n_i}{N_i}\right)_C$$

Table 1.

Fatigue Lives of Specimens Tested at Different Frequencies. Specimens with stress concentration. Amplitude load is 240 lb.

Specimen number	Frequency, Hz	Number of cycles until failure	Time until failure, h	Average failure time, h
1	8	119300	4.14	4.69
2	8	151000	5.24	
3	5	92000	5.11	5.31
4	5	99000	5.5	
5	5	115000	6.39	
6	5	100000	5.57	
7	5	72000	4.01	
8	2	40900	5.68	4.70
9	2	33700	4.68	
10	2	61300	3.74	

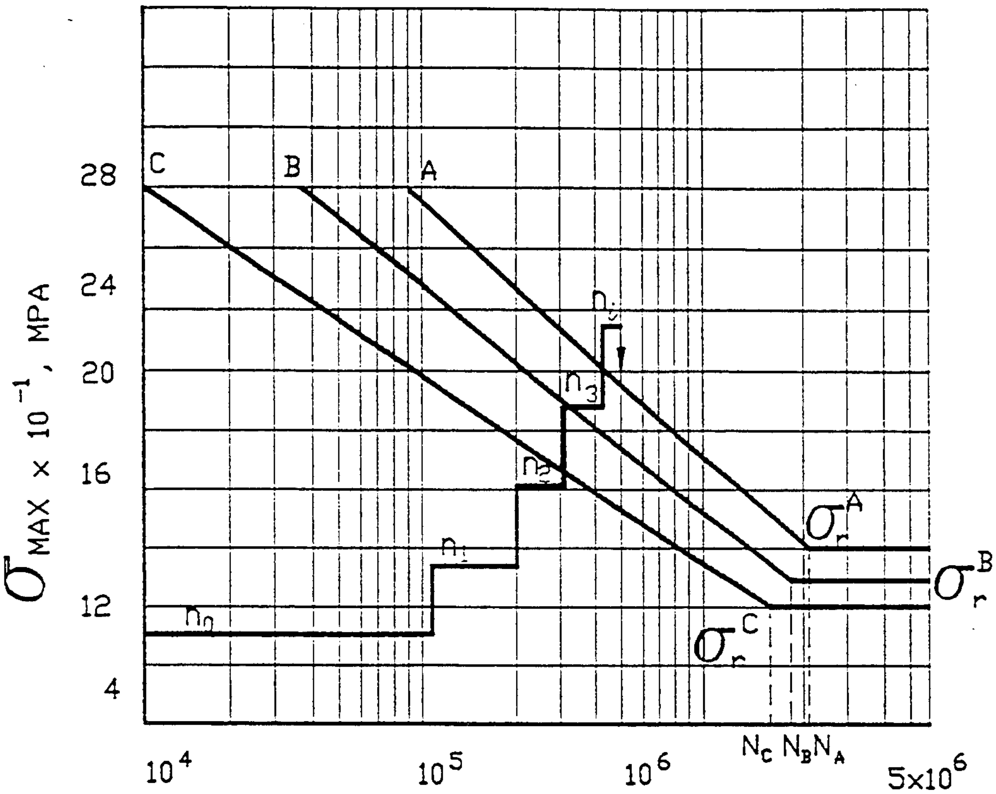


Figure 11. Loading Program for the Accelerated Test. Three fatigue curves A, B, C are received from a long-term fatigue test and correspond, for example, 5%, 50%, and 95% probability of failure

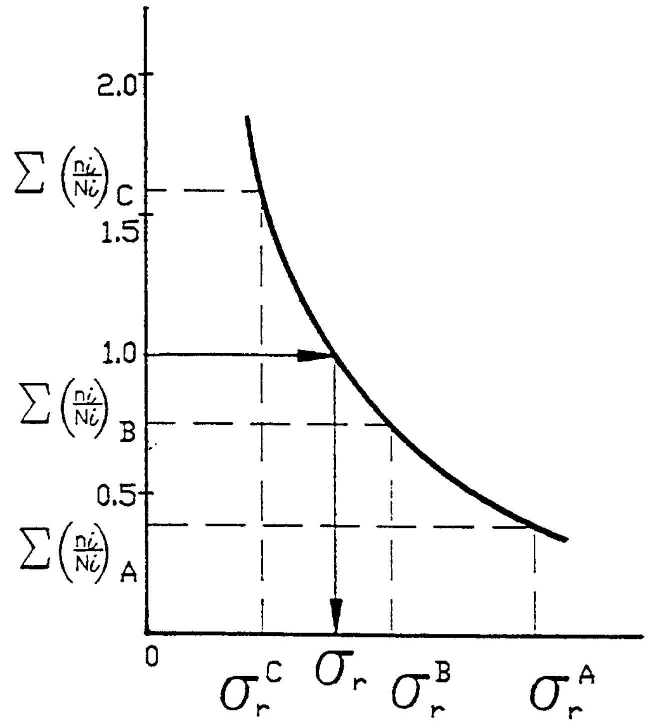


Figure 12. A Diagram for Graphical Determination of Fatigue Strength.

are determined.

With these parameters and the corresponding stresses, we can find the coordinates of the points which result in the curve shown in Figure 12. Now, if according to an accepted hypothesis fatigue strength corresponds to a definite value, it is possible to determine the magnitude of fatigue strength.

The actual long-term fatigue test regimes and results are given in Table 2, and plotted in Figure 13. The example of program and parameters of the accelerated tests and experimental results are given in Figures 13, 14, 15 and 16 and in Tables 3 and 4. The testing lives n are taken from an accelerated test program which is given, for example, in Figure 13, and expected lives N for the curves A, B, and C (90%, 5%, and 95% probability of survival) are taken from Figure 13. The repeatability of the results is quite reasonable and, therefore, the sum of relative lives which is determined experimentally can probably be recommended as a basic parameter to confirm whether the specimens tested during the control procedure belong to the entire population. The time of accelerated tests was never more than 6 hours. The failure damage and failure mechanism during long-term and accelerated fatigue tests were similar. The cracks always started at the bottom tensile zones of the specimens. In all specimens with stress concentrators, the cracks propagated from the hole edges toward the specimens sides. Usually a minute crack spot preceded the crack formation and propagated ahead of the crack tip during the entire process.

Table 2.

Testing Regimes (Long-Term Test, Variable Bending)

Amplitude load LB		Amplitude stress, psi	Min. Stress / Max. Stress	Frequency, Hz
Plate with a hole	Solid plate			
180	240	1440	0.2	12
	360	2160	0.2	8
360	480	2880	0.2	6
	600	3600	0.2	5
540	720	4320	0.2	4
750	990	5760	0.2	3

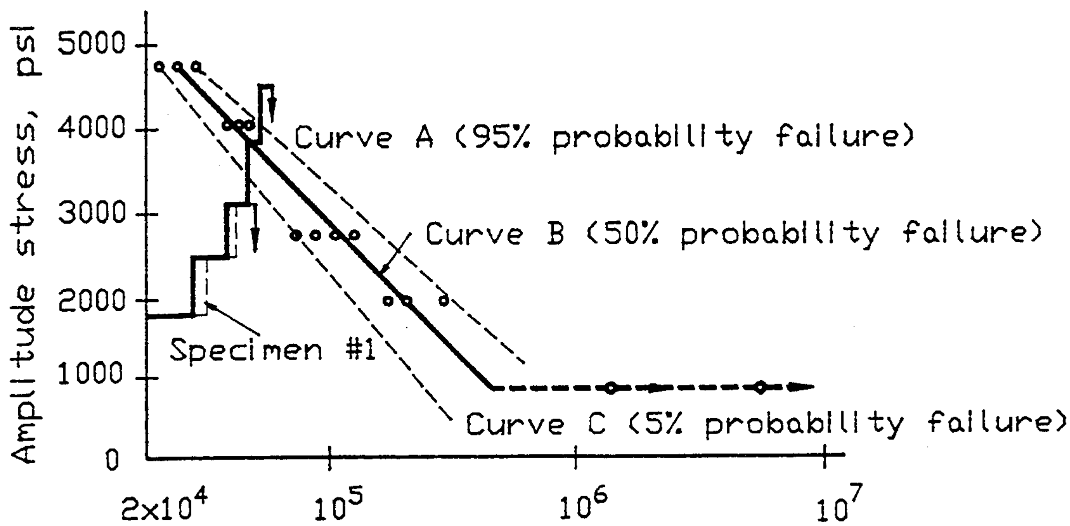


Figure 13. S-N Diagram for Polycarbonate Speciments with Stress Concentrators A, B, C Curves Plotted to Calculate Lives during Treatment of the Accelerated Test Results

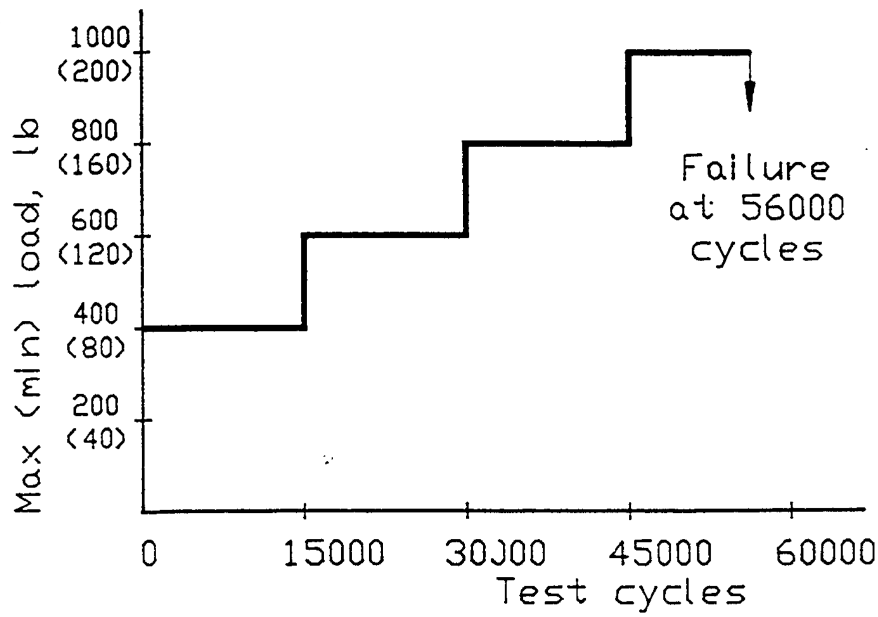


Figure 14. Program and Results of Accelerated Fatige Test. Speciment #1 with stress concentration

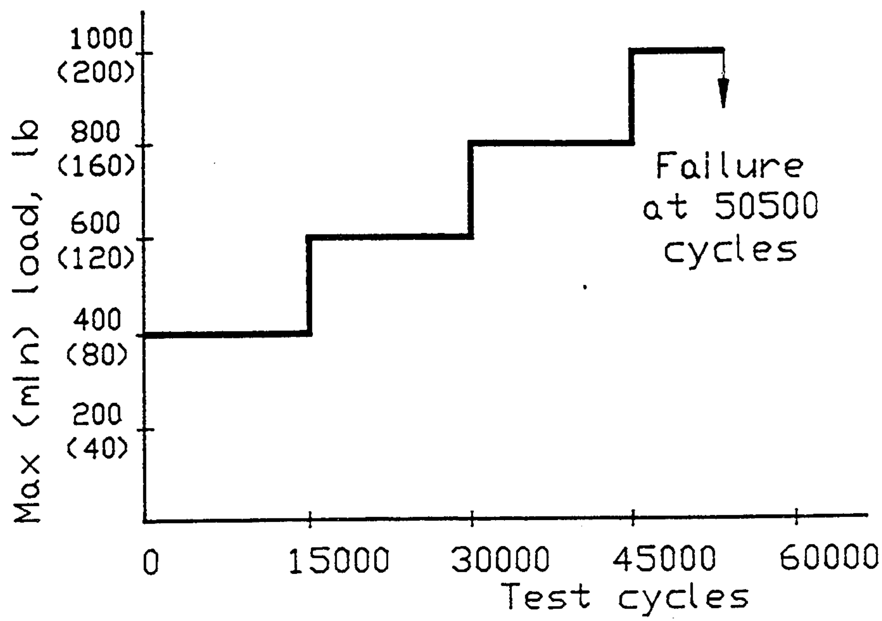


Figure 15. Program and Results of Accelerated Fatige Test. Speciment #3 with stress concentration

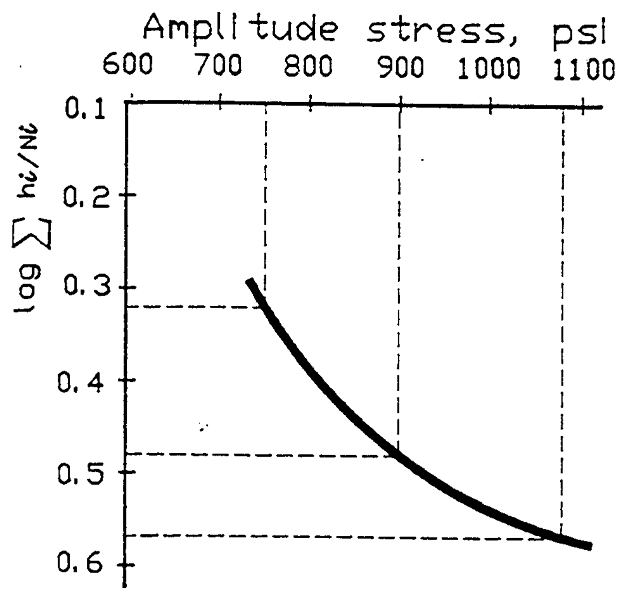


Figure 16. Graphical Representation of the Accelerated Fatigue Test. Specimen #1

Table 3.

Accelerated Test Results.

Specimen number	Max. load increment, Lb	Number of cycles at one load level	Number of steps until failure	Number of cycles until failure
1	200	15000	4	56000
2	200	15000	5	74200
3	200	15000	4	50500
4	200	15000	3	53900

Table 4.

Accelerated Test Result Treatment.

Amplitude stress, psi	Curve A		Curve B		Curve C	
	Ni, cycles	n;/Ni	Ni, cycles	ni/Ni	Ni, cycles	ni/Ni
1280	450000	0.030	350000	0.043	230000	0.065
1920	300000	0.050	260000	0.058	150000	0.100
2560	170000	0.088	140000	0.107	100000	0.150
3200	105000	0.105	85000	0.129	68000	0.162
		0.273		0.337		0.477

8. TEMPERATURE EFFECTS

Flexure fatigue resistance of the 0.5-inch polycarbonate coupons exposed to temperature changes in the range from -50^{o} to 60^{o}C was analyzed.

The test procedure, specimen design, equipment and loading type and regimes were the same as described for the test in laboratory conditions.

The influence of increased temperature (Figures 17 through 22) is very strong, and the fatigue lives of the specimens tested are from 2 to 3 times shorter compared to the test results under room temperature. It is important to note that complete fractures of the coupons tested under increased temperatures followed almost immediately after crack initiations, therefore, there was no "warning" before the break. The fracture surface topography shows (Figures 23 through 27) that it is brittle failure and it is different from the failure under room temperature. Contrary we can observe very significant increase of fatigue resistance under cold temperature. The results of 0.5-inch polycarbonate coupon fatigue tests under cold temperature and comparison of these results with the test data under room and elevated temperatures are given in Tables 5 and 6. The increase was so significant that we can assume that the investigations of the selected material under cold temperature are not critical for the application considered in this project and can be omitted in future.

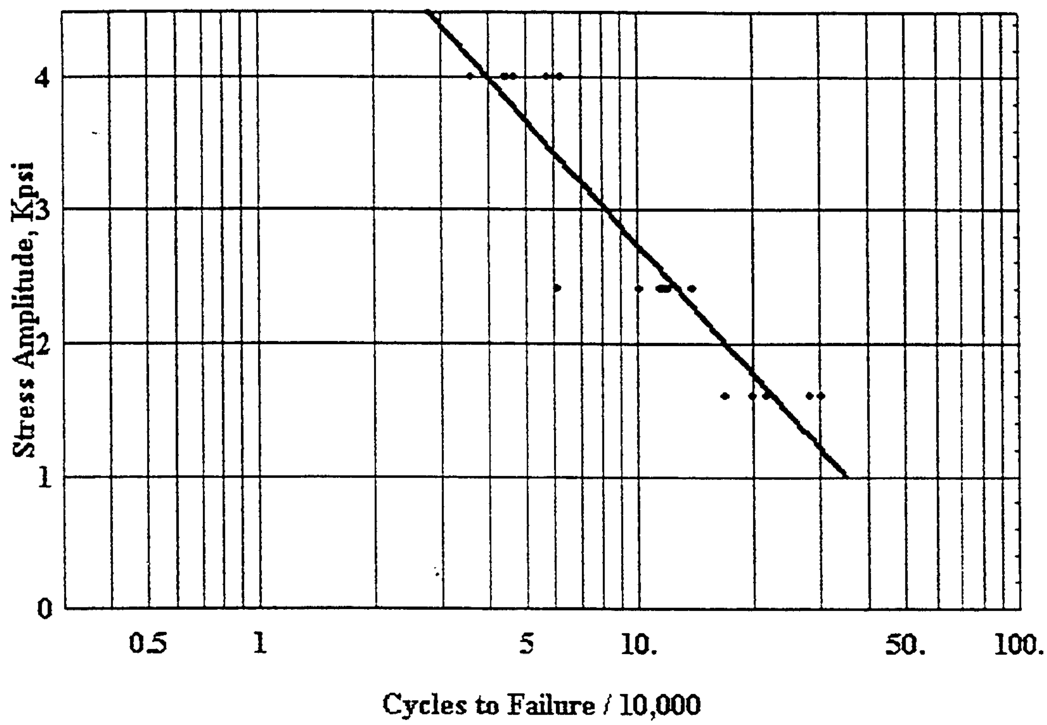


Figure 17. S-N Diagram for the Polycarbonate Specimens Tested Under 30°C

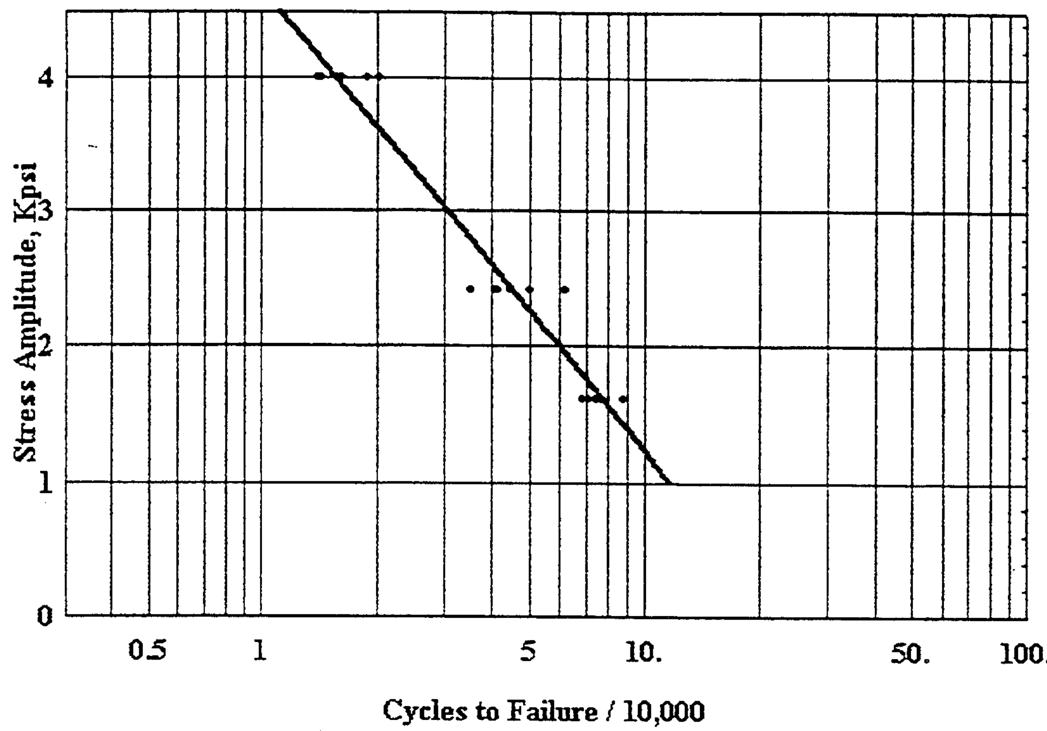


Figure 18. S-N Diagram for the Polycarbonate Specimens Tested Under 40°C.

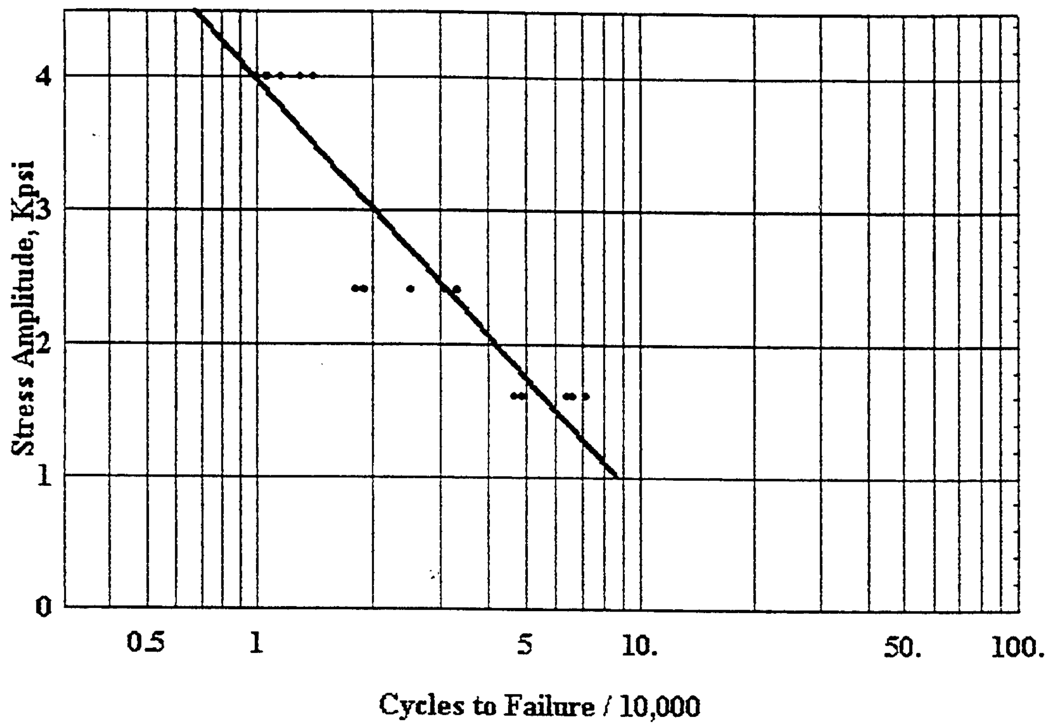


Figure 19. S-N Diagram for the Polycarbonate Specimens Tested Under 50°C

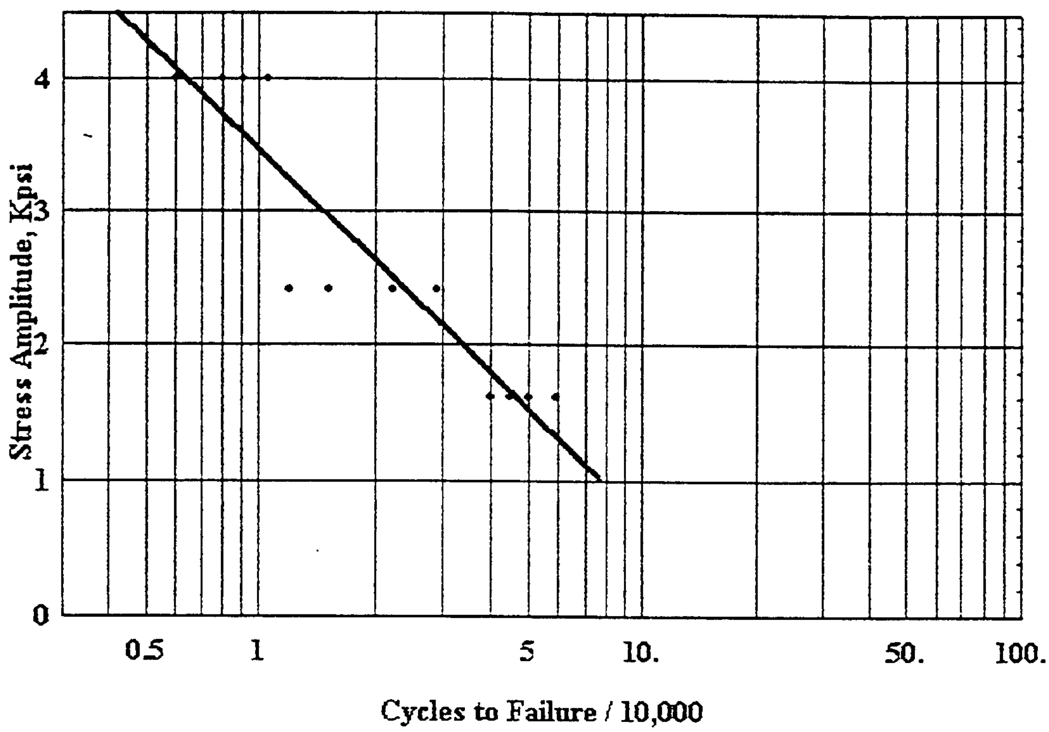


Figure 20. S-N Diagram for the Polycarbonate Specimens Tested Under 60°C

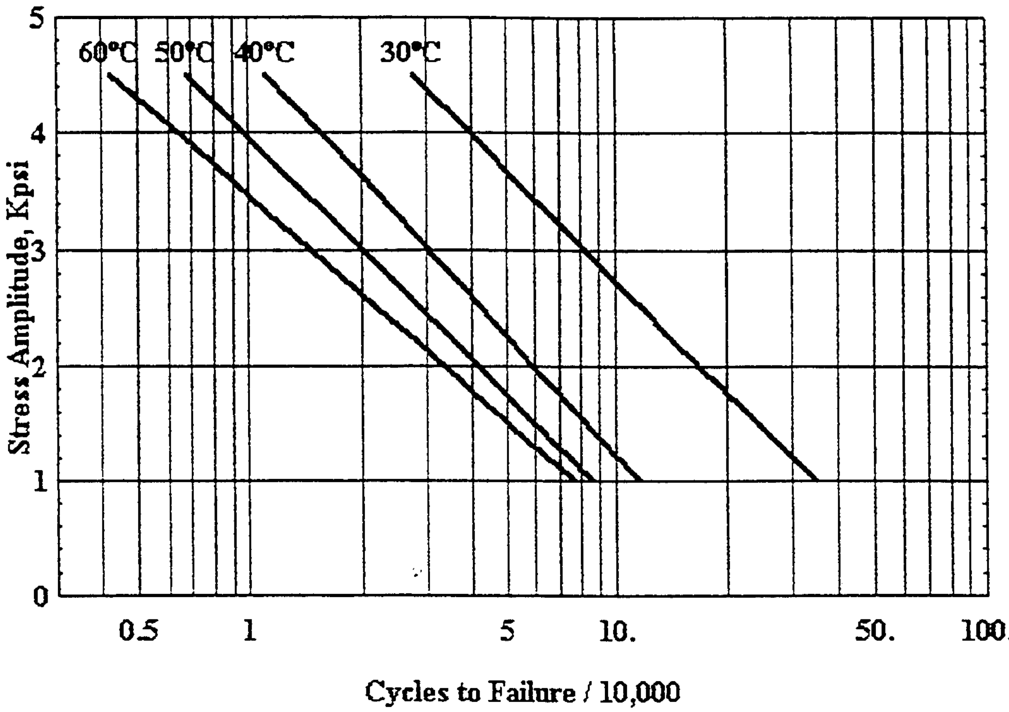


Figure 21. S-N Curves for the 0.5-in Polycarbonate Specimens Tested Under Different Temperatures

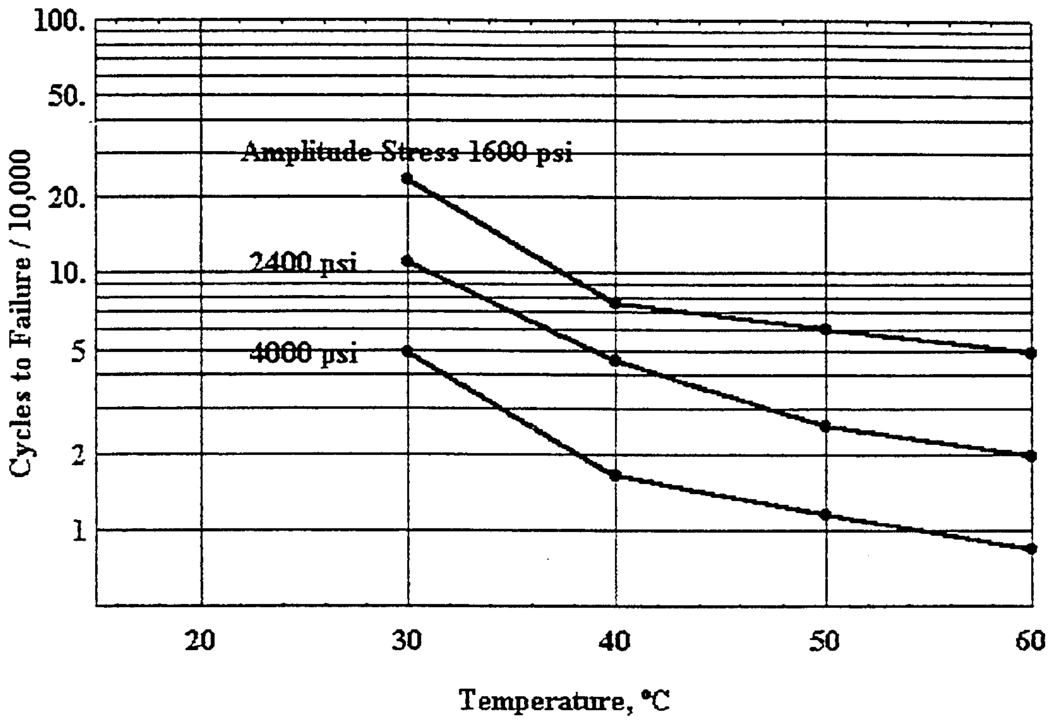


Figure 22. Temperature Effects on Fatigue Life of the 0.5-in Polycarbonate Specimens

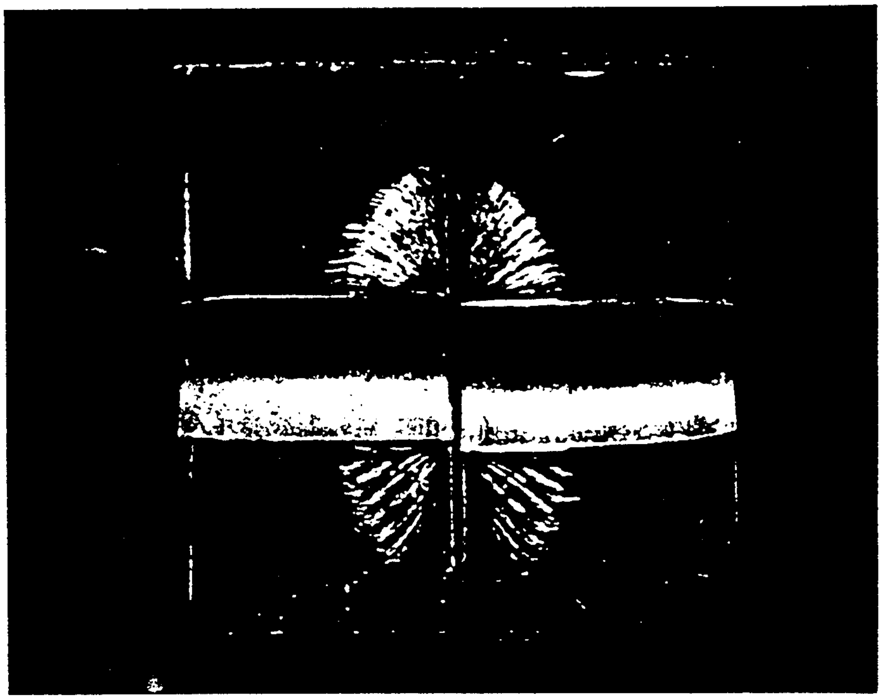


Figure 23. Fracture Surface Topography

Amplitude stress = 1600 psi
Temperature = 40^{o}C
Number of cycles until failure = 71000

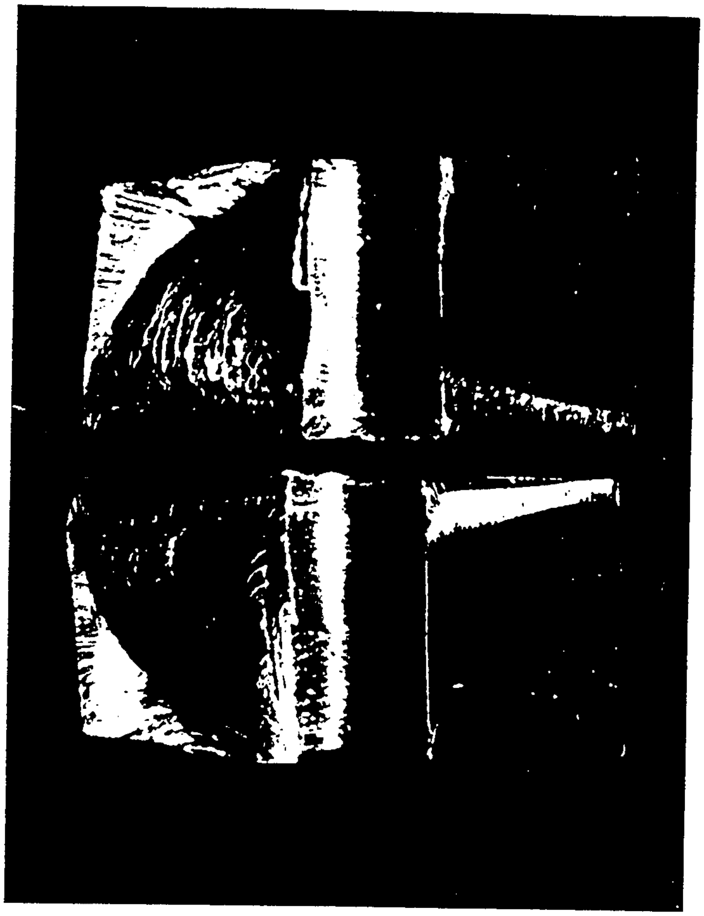


Figure 24. Fracture Surface Topography

Amplitude stress = 1600 psi
Temperature = $50^{\circ}C$
Number of cycles until failure = 29000

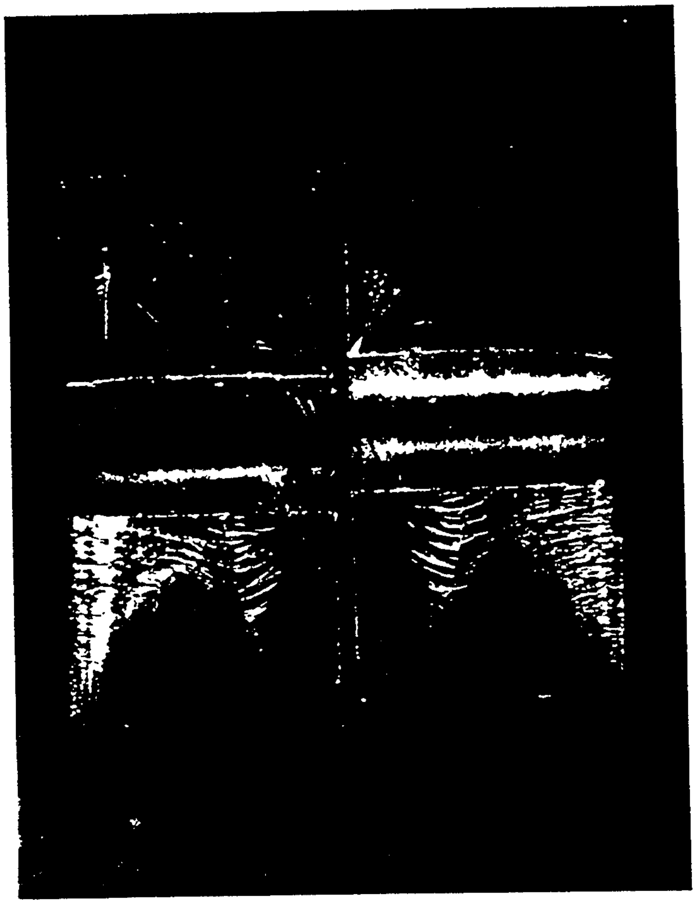


Figure 25. Fracture Surface Topography

Amplitude stress = 1600 psi
Temperature = 60°C
Number of cycles until failure = 53100

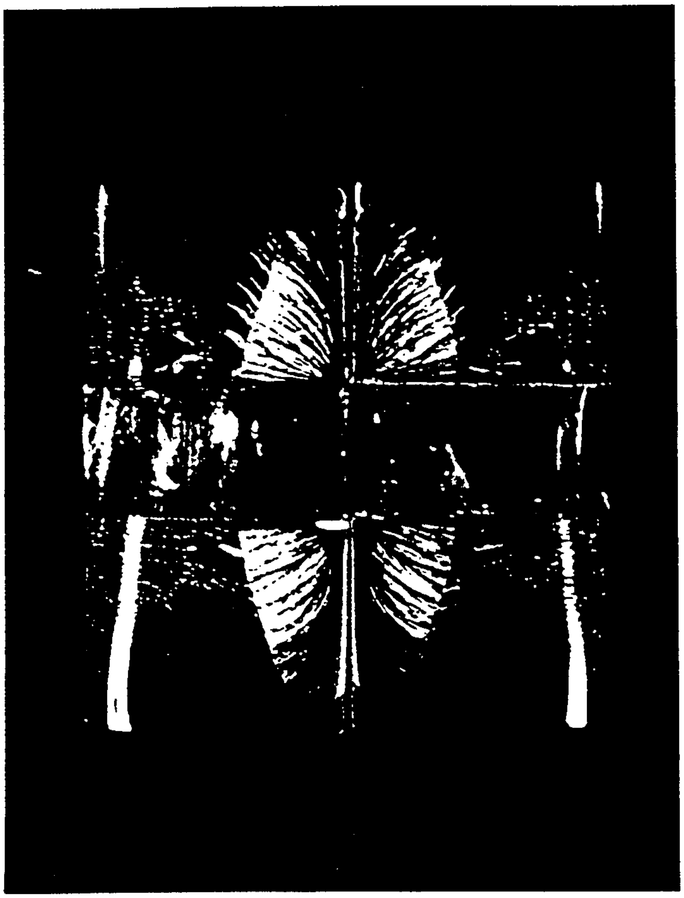


Figure 26. Fracture Surface Topography

Amplitude stress = 2400
Temperature = $30^{o}C$
Number of cycles until failure = 105000

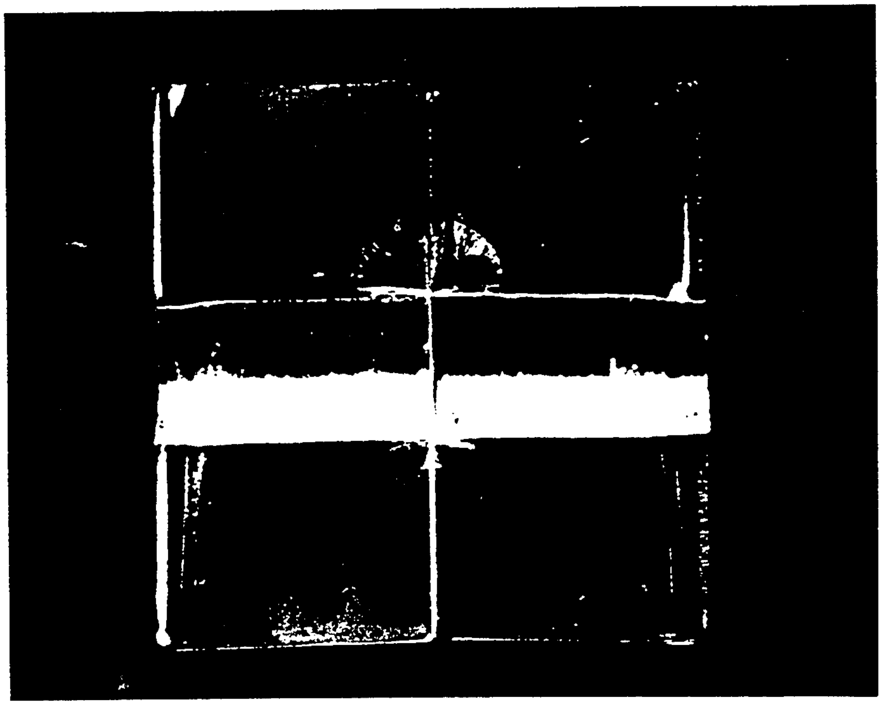


Figure 27. Fracture Surface Topography

Amplitude stress = 2400 psi
Temperature = 60^{o}C
Number of cycles until failure = 19000

Table 5.

Results of 0.5-Inch Polycarbonate Coupon Fatigue Tests under Cold Temperature

Specimen number	Amplitude stress, psi	Temp., C^o	Number of test cycles	Notes
1	6750	-50	119000	Failure
2	6750	-50	132000	Failure
3	4000	-50	100000	No Failure
4	4000	-50	100000	No Failure
5	4000	-50	100000	No Failure
6	2400	-50	100000	No Failure
7	4000	-5	100000	No Failure
8	2400	-5	100000	No Failure
9	2400	-5	100000	No Failure

Table 6.

Comparison of the Fatigue Lives of the 0.5-Inch Polycarbonate Specimens Tested under room, Cold and Elevated Temperatures.**

Amplitude stress, psi	Average number of cycles till failure					
	+30°C	+40°C	+50°C	+60°C	-50°C	-5°C
1600	220,000	80,000	60,000	40,000	-	-
2400	110,000	42,000	26,000	20,000	100,000*	100,000*
4000	45,000	15,000	11,000	8,500	100,000*	100,000*
6750	-	-	-	-	125,000	-

* No Failure
** Laboratory temperature was 30°C

9. CONCLUSIONS

1. The 0.5-inch polycarbonate coupons have substantial fatigue life after crack initiation until complete fracture.

2. The stress concentration effect on the fatigue life of the polycarbonate coupons tested is very strong.

3. The results of the accelerated tests have good repeatability. The procedure can be useful to control the stability of the manufacturing process and for preliminary estimate of new designs.

4. The polycarbonate sheet thickness (from 0.25 inch to 0.5 inch) has a strong effect on the fatigue life of this material.

5. The specimen life in hours does not depend on the testing frequency.

6. The fatigue life of the polycarbonate tested is significantly decreased as the temperature is increased (from 20^{o}C to 60^{o}C).

7. The fatigue life of the polycarbonate is significantly increased as the temperature is decreased from -5^{o}C to -60^{o}C.

8. Investigation of fatigue life of the polycarbonate coupons under combination of factors (alternating load, alternating temperature, periodically applied chemicals, aging) is the area of additional research.

10. REFERENCES

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